Rapid climate change did not cause population collapse at the end of the European Bronze Age

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Short title: End of the Bronze Age not caused by climate change

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Abstract: The impact of rapid climate change on contemporary human populations is of global concern. In order to contextualise our understanding of human responses to rapid climate change it is necessary to examine the archaeological record during past climate transitions. One episode of abrupt climate change has been correlated with societal collapse at the end of the NW

European Bronze Age. We apply new methods to interrogate archaeological and palaeoclimate data for this transition in Ireland at a higher level of precision than has previously been possible. We analyse archaeological ^{14}C dates to demonstrate dramatic population collapse and present high-precision proxy climate data, analysed through Bayesian methods, to provide evidence for a rapid climatic transition at c.750 cal. BC. Our results demonstrate that this climatic downturn did not initiate population collapse and highlight the non-deterministic nature of human responses to past climate change.

Keywords: Climate change: demography; prehistory; Bronze Age; radiocarbon dating

Significance statement: The impact of rapid climate change on humans is of contemporary global interest. Present-day debates are necessarily informed by palaeoclimate studies in which climate is often assumed, without sufficient critical attention, to be the primary driver of societal change. Using new methods to analyse palaeoclimatic and archaeological datasets, we overturn the deterministic idea that population collapse at the end of the NW European Bronze Age was caused by rapid climate change. Our work demonstrates the necessity of high-precision chronologies in evaluating human responses to rapid climate change. It will be significant for geoscientists, climate change scientists and archaeologists.

Introduction

Past population collapse in many parts of the world has been attributed to the direct effects of rapid climate change. Key case studies on the collapse of Anasazi (*1*) and Mayan *(2*) civilizations have attracted considerable public interest due to the concerns over the threat of climate change to contemporary populations. Recent palaeo-environmental studies have identified a major climate shift across much of NW Europe towards the end of the Bronze Age (*3, 4*). This has been associated with socio-economic collapse in Ireland (*5*), northern Britain (*6*), central and western Europe (*7*), and the expansion of Scythian culture into Europe and eastern Asia (*8*).

In NW Europe, the eighth century cal. BC sees the transition from the Late Bronze Age to the Early Iron Age. Whereas evidence for Late Bronze Age settlement and craft production is widespread, it is notoriously elusive for Early Iron Age communities in many parts of NW Europe (*5, 9-11*), suggesting a reduction in population levels. At the same time the international exchange networks required to support bronze-based economies appear to break down. To what extent might these changes be linked to the environmental downturn implied by the palaeoclimate data?

Context

Ireland forms an important study region for examining the relationships between human populations and past climate change. Firstly, the widespread occurrence of peat bogs, containing tephra layers for precise dating and correlation, enables the creation of robust terrestrial climate histories (*12-13*) (Figs. 1, 2, Supplementary Table 1). Secondly, the period from around 1995–2008 saw an enormous upsurge in archaeological activity in Ireland, fuelled by the unprecedented growth of the 'Celtic tiger' economy. Development-led excavations generated enormous quantities of new data, including ^{14}C dates from a broad range of landforms and environments across the island (Fig. 1). The archaeologically untargeted nature of this work means that this ^{14}C dataset is unbiased by the interests and pre-occupations of archaeologists to a degree that is unique globally (*14*).

There have been previous attempts to correlate archaeologically-defined levels of human activity in prehistoric Ireland with palaeoclimatic proxy records, comparing summed ^{14}C dates of archaeological activity with a climate index inferred from bog oak population dynamics (*15*). However, bog oak population dynamics have been shown to be an unreliable record of past climate (*16*). There have been other attempts to link rapid climate change to human societal changes (*8*); however, establishing clear causal links between humans and climate change is difficult due to the problems of establishing an accurate, precise chronological framework (*17*).

Summed probability functions (SPFs), which involve the 'summing' of large numbers of ^{14}C dates, have been used as a proxy for human population in numerous recent studies (*18*-*19*), although their reliability has sometimes been questioned on the grounds that artificial peaks and troughs introduced by the calibration process irretrievably distort the 'real' patterns (*20*-*21*). It has been demonstrated that real patterns can be observed in SPFs through statistical analysis with randomly generated data (*14*), as well as comparison with dendrochronologically dated phases (*17*). Use of these methods enables us to observe genuine fluctuations in human activity and compare these directly with the palaeoclimate data.

Results and discussion

We examined 2023 archaeological radiocarbon dates from Ireland spanning the period 1200 cal. BC to 400 cal. AD (*14*, Supplementary Table 2). For the period 1200 cal. BC to 500 cal. BC the results (Fig. 3) demonstrate clear patterns in relative levels of human activity that appear to reflect demographic fluctuations (*14*). There appears to be a distinct peak in human activity in Ireland at around 1050-900 cal. BC, followed by steady decline to around 800 cal. BC, and a rapid fall to 750 cal. BC. Our analysis (*14*) shows that the pattern in the archaeological SPFs cannot be explained by random variations (Fig. 3). This analysis is supported by the regional pollen records which identify a peak in farming activity in the late 11th century BC followed by a decrease during the ninth to early eight centuries BC (*22-23*). To evaluate whether or not climate change instigated the observed demographic changes, we analyse high resolution proxy climate data from Ireland alongside the archaeological evidence (Fig. 3). A major, rapid climate deterioration (shift to much wetter conditions) is registered in testate amoebae-based water table reconstructions and humification records from peatlands in Ireland, and has been precisely dated to c. 750 cal. BC (*24*). At the best dated site (Glen West bog, County Fermanagh), the start of this shift has been constrained using a Bayesian age-depth model to 748 cal. BC (maximum probability) or 703-786 cal. BC (modelled range). The timing of the shift has been linked by tephrochronology to several other peatland sites in Ireland (*25*, Fig. 2) and independently dated by ^{14}C to 791-429 cal. BC (Derragh Bog, County Longford) (Supplementary Figure 1). The precise tephra-framed replication of this event in several different peatlands suggests that it is a reliable widespread response of peatland hydrology to a rapid increase in precipitation and/or decrease in temperature, rather than related to internal peatland dynamics (*26*). A climate shift at c. 800-750 cal. BC is also seen across NW Europe and is potentially the most profound climatic shift of the Mid- to Late Holocene prior to the Little Ice Age (*3*, *27*, *28*).

Comparison of the archaeological and palaeoclimate data demonstrates that the decline in population at the end of the Bronze Age began more than a century prior to the climatic downturn of the mid-eighth century BC (Fig. 3). Therefore the decline can be categorically disassociated with the climate downturn. To explain the end of the Bronze Age we must look instead towards socio-economic factors. Bronze-based economies relied on complex, long-distance trade networks to bring together the raw materials necessary for bronze production. Control of these networks appears to have formed the basis of social power in Bronze Age Europe and promoted the development of complex, hierarchical social structures (*29*). It has long been argued that the widespread availability of iron ores fatally undermined these social structures by democratizing access to metals (*30*). The adoption of iron technology thus made redundant the long-established networks that underpinned Late Bronze Age society. Resultant social destabilization may well be the cause of the population collapse at the end of the Bronze Age. Against the background of contemporary debates it is easy to view climate as the primary driver of past cultural change. Such assumptions need to be critically assessed using high-precision chronologies to guard against misleading correlations between unrelated events.

Materials and Methods:

^{14}C dates were collected by collating the published and unpublished literature for prehistoric Ireland and by written requests for information to all active commercial and research-based archaeological groups in Ireland (*31*). A total of 2023 ^{14}C (Supplementary Table 2) dates meeting appropriate quality thresholds (*32*) were used to create a SPF, with a further 78 being excluded as they did not meet the threshold and a further 157 excluded as not enough information to judge their quality was available. The graphics in this paper represent the period of interest from 1200 cal. BC to 500 cal. BC (graphic representation of the full dataset is provided in *14*). Since few sites have produced substantial numbers of dates, and few are phased in the conventional sense, it was neither necessary nor practical to adopt the approach of Collard et al (*33*) of summing dates for particular phases in order to avoid inter-site biases in the overall quantities of dates. We generated random simulations of calendar and ^{14}C ages as null hypotheses to test the summed archaeological dates against. We used a distribution-less random number generator (using R: R Core development team (*34*)) and the same number of dates as in the archaeological dataset (n = 2023). For the calendar year simulation, a random series of calendar years were calculated and converted to simulated ^{14}C determinations in OxCal (*35*). Each simulated determination was attributed a random error of between 20 and 80 years. We used the running correlation method of Armit et al (*14*) to examine periods of correlation and non-correlation between the random simulations and the archaeological data. In addition we subtracted the random simulations from the archaeological data (*14*).

Previous Holocene palaeoclimate studies in Ireland, including those based on lake and speleothems (*36*, *37*), lack the chronological resolution needed for examining human-environmental relations at centennial scales. It has also been suggested that narrow ring events in bog oaks signify extreme, rapid environmental change at 2345 cal. BC, 1628 cal. BC, 1159 cal. BC, 207 cal. BC and cal. AD 540 (*38*), however, the climatic meaning of these has still to be determined. Palaeoclimate reconstructions from peatlands reflect past changes in the length and intensity of the summer water deficit, most probably controlled by summer precipitation in oceanic NW Europe (*39*). In Ireland, published high-resolution records based on peat humification and testate amoebae-based water table reconstructions were chosen for this investigation (*40, 41*). Water table reconstructions were carried out using the European transfer function (*42*) for Dead Island, Derragh, Glen West (high-resolution section only) and Slieveanorra bogs. These records are dated by ^{14}C, tephrochronology and spheroidal carbonaceous particles. Tephra layers provide a robust chronological framework for precise comparison and correlation of the records in time (*25*). The chronologies and associated errors for the water table reconstructions were modelled using Bacon, an age-depth model based on piece-wise linear accumulation (*43*), where the accumulation rate of sections depends to a degree on that of neighbouring sections. The total chronological error (difference between maximum and minimum probability ages at 95%) associated with each depth (in all the above sites) was calculated from the model. These records have centennial to sub-centennial chronological resolution.

The water table data were standardised to z-scores, combined and ranked in chronological order (i.e. by maximum age probability as modelled by Bacon). LOWESS (Locally weighted scatterplot smoothings (*44*) (smooth = 0.02 and 0.1) were calculated (Supplementary Table 3). Polynomial regressions in a neighbourhood of x were fitted following:

$$n-1\sum_{i=1}^{n} W_{ki}(x)\left(y_i-\sum_{j=0}^{p}\beta_j x^j\right)^2$$

Where $W_{ki}(x)$ denoted k-NN weights (*45*), bootstrapping was used (999 random replicates) to calculate 95% error ranges on the high-resolution LOWESS function (smooth = 0.02). In order to retain the structure of the interpolation, the procedure used resampling of residuals rather than resampling of original data points. It was found that interpolation to annual interval made little difference to the overall shape of the LOWESS function. This function represents a statistical compilation of the peatland water table records and models the inter-site events. It can be used as an exploratory tool to assess overall trends in the data but the interpretation of wet and dry shifts is based on a consideration of the individual site records.

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I.A., G.S. and K.B. conceived the project and collaborated on the development of methods to synthesise, present and interpret the ^{14}C data. K.B. collected and processed the archaeological ^{14}C data. G.S. collected the palaeoenvironmental data and carried out the statistical analysis. G.P.

synthesised and interpreted the pollen data and M.B. assisted with age-depth modelling. All authors contributed to the writing of the manuscript.

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Figure legends:

Figure 1. Map of Ireland showing relevant archaeological sites and locations of peatlands used to derive the climate proxy data (see Table S1); (1) Dead Island; (2) Derragh; (3) Garry; (4) Glen West; (5) Lough Lurgeen; (6) Moyreen; (7) Owenduff; (8) Slieveanorra; (9) Sluggan. The linear distributions visible in many of the archaeological sites reflect their discovery through road and pipeline schemes.

Figure 2. Proxy climate data from Irish peatlands for the period 1200 BC – AD 400. Humification data and testate amoebae-based water table reconstructions are shown. Tephra layers, used for correlation and dating, are illustrated. The combined data are shown alongside the total modelled chronological error (from the Bacon models – Supplementary Figure 2). LOWESS models (smooth = 0.02 and 0.1) illustrate the major common features of the proxy climate compilation (errors are a 95% bootstrap range on the 0.02 model). Humification data are expressed as residuals; the reconstructions are expressed as water table depth below the peat surface and are based on the transfer function of Charman et al (*29*).

Figure 3. (A) Summed probability function (SPF) of the archaeological data with SPFs based on simulated series of dates in ^{14}C and calendar years. This illustrates clearly that the features in the archaeological SPF cannot be the product of random variations. (B) Running correlation coefficient between the archaeological and simulated SPFs. (C) LOWESS models (smooth = 0.02 and 0.1) illustrating the major features of the proxy climate compilation (errors are a 95% bootstrap range on the 0.02 model, see Fig. 2). (D) The archaeological SPF minus both simulated series (in A) compared with the LOWESS models.

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Figures and Tables:

Figure S1. Modelled age range of the shift to wetter conditions in four key peatlands (refer to Bacon models in Supplementary Figure 2).

Figure S2. a-d Bacon age-depth models for the peatland sites.

Table S1. Peatland sites used to derive the proxy climate records.

Table S 2. Archaeological ^{14}C data. This is the entire dataset, on which the overall reconstruction (Armit, Swindles and Becker 2013, Ref 14 in main bibliography) is built.

Table S3. Hydroclimate Data

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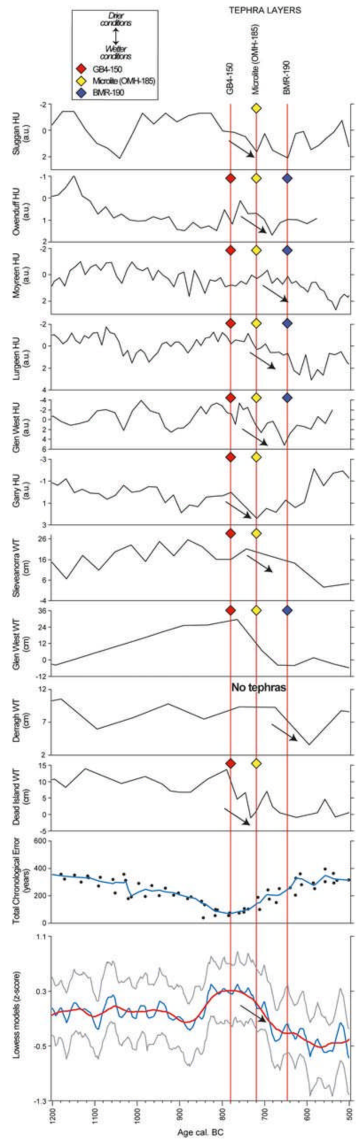
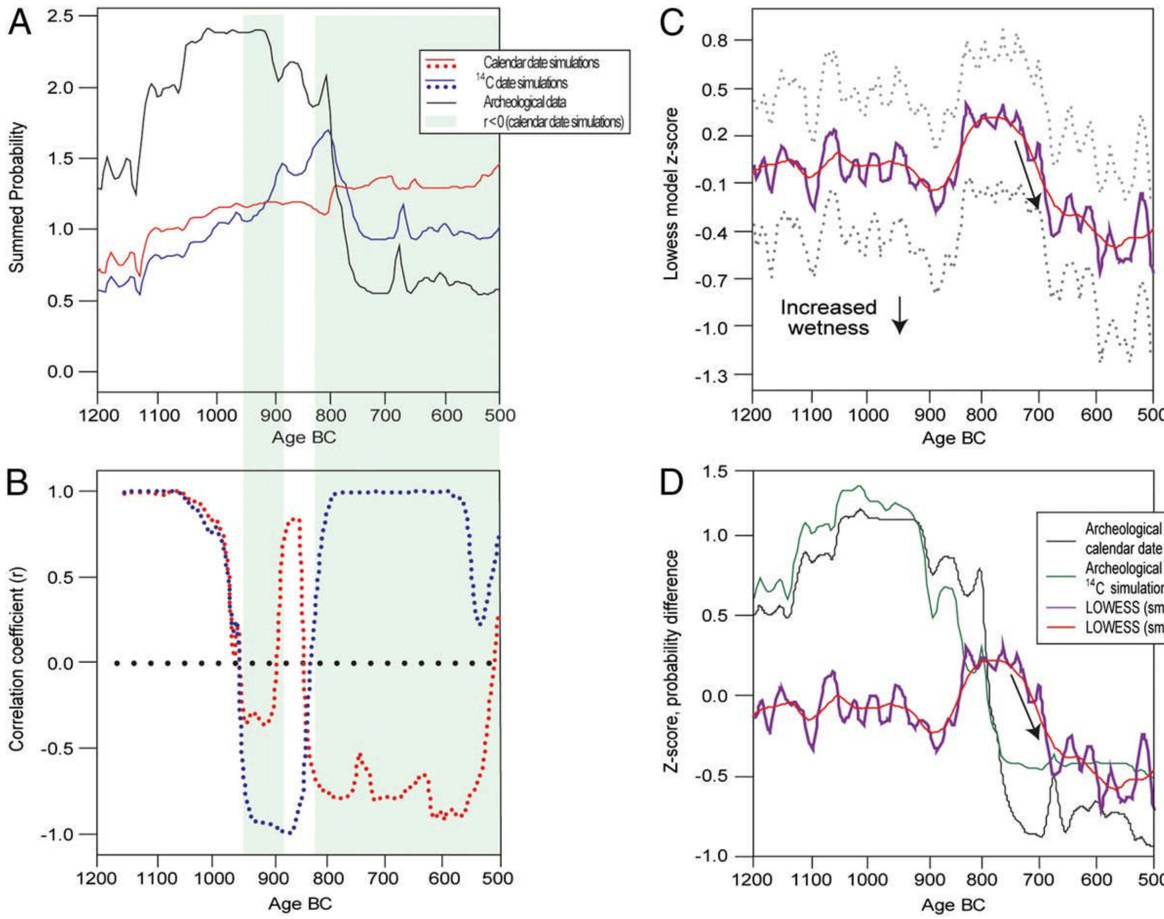
Archaeological site
Palaeoclimate site
1
2
3
4
5
6
7
8
9
N
0
100km
Source: Esri, DigitalGlobe, Earthstar Geographics, CNES/Airbus DS, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community



TEPHRA LAYERS
Drier conditions
Wetter conditions
GB4-150
Microlite (OMH-185)
BMR-190
Sluggan HU (a.u.)
Owenduff HU (a.u.)
Moyreen HU (a.u.)
Lurgeen HU (a.u.)
Glen West HU (a.u.)
Garry HU (a.u.)
Slieveanorra WT (cm)
Glen West WT (cm)
Derragh WT (cm)
No tephras
Dead Island WT (cm)
Total Chronological Error (years)
Lowess models (z-score)
Age cal. BC


A
B
C
D
Summed Probability
Correlation coefficient (r)
Lowess model z-score
Z-score, probability difference
Age BC
Calendar date simulations
14C date simulations
Archeological data
r < 0 (calendar date simulations)
Increased wetness
Archeological data minus calendar date simulations
Archeological data minus 14C simulations
LOWESS (smooth = 0.02)
LOWESS (smooth = 0.1)